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Authors
Chen, Yu
Abel, Kingsley Travis
Janecek, John T
et al.

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Home-based technologies for stroke rehabilitation: A systematic review

Yu Chen[a,*], Kingsley Travis Abel[b], John T. Janecek[c], Yunan Chen[b], Kai Zheng[b], Steven C. Cramer[d]

[a] School of Information Systems and Technology, San Jose State University, United States
[b] Department of Informatics, University of California, Irvine, United States
[c] Department of Computer Science, University of California, Irvine, United States
[d] Department of Neurology, University of California, Irvine, United States

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ABSTRACT

Background: Many forms of home-based technology targeting stroke rehabilitation have been devised, and a number of human factors are important to their application, suggesting the need to examine this information in a comprehensive review.
Objective: The systematic review aims to synthesize the current knowledge of technologies and human factors in home-based technologies for stroke rehabilitation.
Methods: We conducted a systematic literature search in three electronic databases (IEEE, ACM, PubMed), including secondary citations from the literature search. We included articles that used technological means to help stroke patients conduct rehabilitation at home, reported empirical studies that evaluated the technologies with patients in the home environment, and were published in English. Three authors independently conducted the content analysis of searched articles using a list of interactively defined factors.
Results: The search yielded 832 potentially relevant articles, leading to 31 articles that were included for in-depth analysis. The types of technology of reviewed articles included games, telerehabilitation, robotic devices, virtual reality devices, sensors, and tablets. We present the merits and limitations of each type of technology. We then derive two main human factors in designing home-based technologies for stroke rehabilitation: designing for engagement (including external and internal motivation) and designing for the home environment (including understanding the social context, practical challenges, and technical proficiency).
Conclusion: This systematic review presents an overview of key technologies and human factors for designing home-based technologies for stroke rehabilitation.

1. Introduction

Stroke is a leading cause of serious and long-term disability in the United States [1]. After the initial days-weeks of inpatient treatment at an acute care then inpatient rehabilitation facility, patients with stroke still have a long and tedious recovery process in front of them, involving return of physical, speech, cognitive, and other functions. With the advance of information technologies (IT), numerous studies have investigated the feasibility and effectiveness of new IT tools and their design towards the purpose of facilitating rehabilitation after stroke [2–12]. For example, systematic reviews have examined the outcomes of robot-assisted therapy [2–10]. Telerehabilitation, which allows patients to conduct therapy with therapists using telecommunication technology, has been widely deployed for stroke recovery in a number of reviews [10,11,13]. Virtual reality has also been used in post-stroke therapy, and researchers have systematically studied clinical effects of commercially available virtual reality games [12], the effectiveness of virtual reality therapy in upper limb motor functions [14], balance control and gait [15,16], lower limbs [17], and walking [18].

In parallel, there has been an increasing amount of work that leveraged information technologies to help patients conduct rehabilitation *at home*. Home-based technologies have the advantage of providing flexibility of location and time in rehabilitation therapy and remotely receiving feedback from therapists. However, to the best of our knowledge, a systematic literature review on information technologies for stroke rehabilitation in the *home environment* has not been published previously. Further, most systems and studies evaluate the success of a system by the clinical outcome [4,9] such as motor and functional abilities [17]. However, use of rehabilitation technologies in the home environment, independently, is a complex process, and very few works have systematically addressed *patients' requirements* – beyond clinical requirements – in designing IT tools for stroke rehabilitation [11]. To

* Corresponding author at: School of Information Systems and Technology, Lucas College and Graduate School of Business, San Jose State University, United States.
E-mail address: yu.chen@sjsu.edu (Y. Chen).

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this end, we conducted a systematic review of information technologies that are designed to help stroke patients conduct rehabilitation at home. Our primary goals were to understand 1) the types of technologies used for home-based rehabilitation after stroke and 2) design requirements for such technologies.

2. Methodology

2.1. Search strategy

Keywords, databases, and search strategies were iteratively selected based on review of current systematic review articles. From January 30th to April 30th, 2017, we conducted a systematic literature search in the following three electronic databases: PubMed, ACM Digital Library, and IEEE. We also searched secondary references of the resultant articles to identify additional relevant literature. The search strategy included three types of keywords: stroke rehabilitation, home-based, and technologies. These keywords needed to appear in conjunction in the title, abstract, or full text of the article. The full list of words used is listed in Appendix A. We removed duplicate citations across databases using Zotero and conducted a manual revision for verification.

2.2. Inclusion and exclusion criteria

We included studies published in peer-reviewed journals and conference proceedings in English. The technologies needed to be directly related to stroke rehabilitation at home. The studies had to be conducted at patients' homes and based on an empirical design. Systems that were not evaluated, only evaluated in the laboratories or clinical setting instead of the home environment or evaluated in healthy adults were not included in the review. If a study was reported in more than one article and presented the same data, we only included the most recent publication. However, if new data were presented in multiple articles describing the same study, all were included.

2.3. Screening and data extraction

Two authors (YC1 and JTJ) screened all titles and abstracts of all articles identified through the search strategy. Then the two reviewers independently reviewed the full text of pre-selected articles and agreed on the final set of articles through discussion.

2.4. Data synthesis and analysis

Three authors (YC1, JTJ, and KTA) independently performed data extraction. An abstraction template and a data dictionary were developed by consensus and iterative review of the team, including year of publication, country, technology used, study design, participants, measurements, and main findings (Tables B1, C1, D1). The authors coded the articles according to the categories in the template. The first author re-reviewed all the articles as a verification step. Quality of studies was not considered in these analyses.

3. Results

3.1. Included studies

In total, we identified 847 articles: 34 articles from ACM, 218 from IEEE, and 595 from PubMed for a full-text review (Fig. 1). After removing duplicates, the initial set consists of 832 articles. Among them, 169 were chosen as highly relevant by two reviewers. In the end, 31 articles with 25 systems were analyzed in detail (Table 1).

3.2. General overview

The included articles were published between 2004 and 2017. They represented 25 projects: 14 [22–36] conducted in the United States, 12 [37–53] in Europe (including the United Kingdom, Sweden, Italy, Switzerland, the Netherland), 1 [54] in New Zealand, and 1 [55] in China. The following types of technologies emerge in the articles: games (14 projects), telerehabilitation (8 projects), robotic devices (7 projects), virtual reality (6 projects), wearable sensors (4 projects), and tablets (2 projects). Each project leverages one or more types of technologies. Among the selected projects, 12 adopted a quantitative design, 2 used a qualitatively method, and 11 used a mix of quantitative and qualitative approach.

3.3. Technologies

In this subsection, we present the definitions, projects, benefits and limitations of commonly used technologies in home-based stroke rehabilitation systems (Table B1).

3.3.1. Games

Conducting rehabilitation through playing games makes the repetitive exercises more engaging and motivating. A total of 14 projects [23,24,26,29,31,35,37,40,42,46,49,50,53,54] deployed games for home-based stroke rehabilitation systems. Among them, two projects [42] leveraged general commercial games not specifically designed for rehabilitation (i.e., Nintendo Wii Sport [40], Sony PlayStation 2 [29]). The main advantages for using commercial games are the acceptability and affordable prices, but they may not contain sufficient guidance for, or measurement of, the movement and position of the arms, hands, and fingers to serve accurate and useful therapeutic purposes. Meanwhile, the other 13 projects developed games specifically for stroke rehabilitation purposes to offer adaptive and personalized exercise programs. To effectively detect and track patient movement in the exercises, such games usually integrate robotic devices or motion sensors, such as Wii mote [40], Kinect [50], ArmeoSenso53. Designing stroke rehabilitation games provides more targeted exercises for patient recovery and for therapists to evaluate the progress than general commercial games, but might require technical training and learning progress for patients to adopt new games.

3.3.2. Telerehabilitation

Telerehabilitation [23,27,32–34,52,55], also referred to as teletherapy or tele-stroke, uses information and telecommunication technologies, such as telephone and video conferencing, to help patients receive medical services from health providers remotely [23,52]. The technical functionalities of telerehabilitation is usually achieved through video conferencing and includes the capability for therapists to observe patients' movement when executing rehabilitation tasks. Telerehabilitation has the potential to reduce the duration of inpatient hospitalization by helping patients conduct rehabilitation at home, and thus reducing costs [52,55]. Telerehabilitation is particularly useful for stroke patients who are underinsured, have difficulty with transportation, depend on caregivers, or lack stroke rehabilitation services in their geographic areas [23]. Researchers have also identified a number of limitations for using telerehabilitation for stroke recovery [51], such as the lack of physical interaction between patients and therapists and in some instances the requirements for technical proficiency to use the telerehabilitation services. Moreover, key policy challenges with home-based telerehabilitation are yet to be fully understood, e.g., the cost, reimbursement, privacy, liability, and system security [23].

3.3.3. Robotic devices

[23,28,32,36,37,46,47] replace, or in some cases augment, manual rehabilitation provided by healthcare professionals with automated motor assistance. The robotic devices mainly aid the movement of the arm, wrist, and hands to improve the active flexion and extension range of motion. Robot-assisted therapy that uses an exoskeleton approach may provide similar or additional benefits for hand motor function in

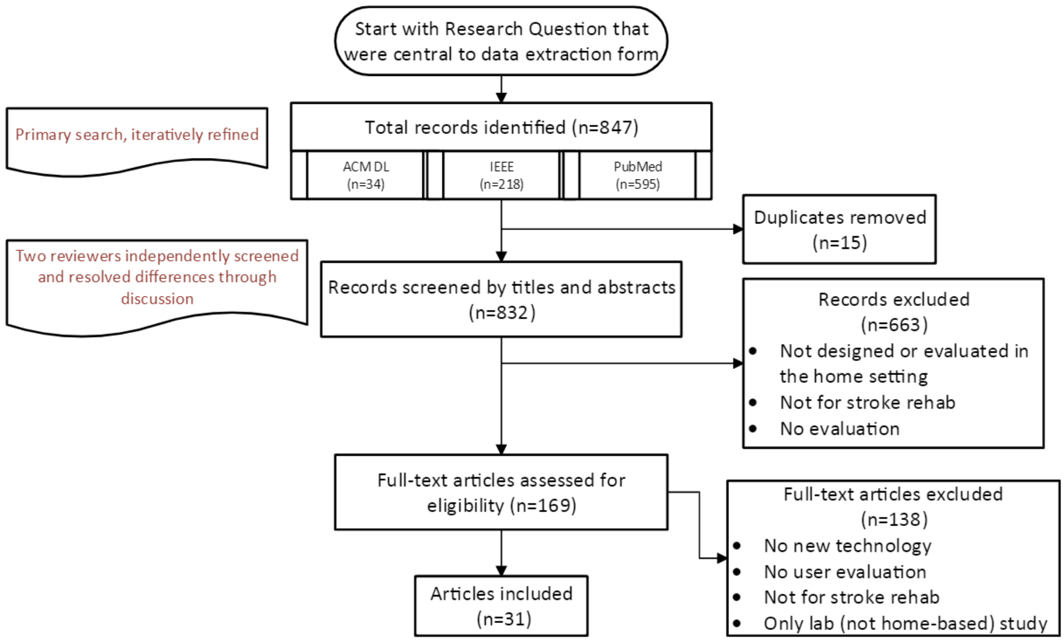

Fig. 1. Flow diagram of the Screening Process.

Table 1
Summary of the 31 included articles and projects (Note: some systems used multiple types of technologies).

	N	%
Technologies used (25 systems)		
Games	14	34
Telerehabilitation	8	20
Robotic devices	7	17
Virtual reality	6	15
Sensors	4	10
Tablets	2	5
Types of evaluation (25 systems)		
Quantitative	12	48
Qualitative	2	8
Mixed of quantitative and qualitative	11	44

comparison with conventional therapy in patients with chronic stroke [56], though uncertainty remains regarding the effect size of such treatment approaches. A variety of robotic devices were used, such as robotic arms [37] and robotic exoskeleton system [28]. Some integrated commercial robotic devices, e.g., Saebo Mobile Arm Support (SaeboMAS) 46], Haptic Master [47], Hand Mentor Pro (HMP) [23], Hand Mentor [32], and Myomo mPower 1000 [36]. Robotic devices automate therapy procedure and generate a wide variety of forces and motions for training [28]. Another benefit of robotic devices [5] is to deliver measurable and optimal dose and intensity for intensive therapy [23]. Despite the benefits, robotic devices usually require large physical space in the living environment and sometimes appropriate facilitates such as tables and chairs for setup. This is particularly challenging for participants living in a crowded space [32]. Some robots generate large forces at times that can create theoretical safety concerns when used unsupervised in the home.

3.3.4. *Virtual reality*

[28,29,40,52–54] devices use computing technologies to provide virtual environment that simulates the physical environment. Virtual reality has emerged as a recent approach for providing stroke rehabilitation therapy [40]. Virtual reality devices are usually designed as interactive games or virtual exercises. For example, the Virtual Glove [41] provides games that require rehabilitative movement of the hand to navigate through obstacles and interact with a virtual balloon, and of the fingers to release a ball to hit a target. Other virtual reality systems transform rehabilitation exercises into tasks in the virtual space. Piron et al. [51] reported a system that transformed therapist's tasks (e.g., pouring water and using a hammer) and the patient moved the real object following the trajectory of the corresponding virtual object displayed on the screen. Similarly, the other training systems [28,53] designed pointing task training that encourages patients to reach virtual targets with their impaired arm. Overall, virtual reality provides patients a safe and controlled virtual environment that might later be applied to a real-life context. Patients can practice and receive feedback about their activities [29] without having to worry about mistakes. However, the challenge lies in validating the clinical outcome of solely using virtual reality devices, particularly those not specifically designed for rehabilitation. Also, sensory feedback, so critical to brain plasticity and rehabilitation therapy gains, can be altered or reduced with virtual reality approaches.

3.3.5. *Sensors*

[39,46,53,55] are usually deployed to measure patients' exercise movement and provide feedback. In addition to sensors commonly used in commercial games, such as Kinect [26,35,50] and Wiimote31 [41,42], a wide range of other sensors have been investigated. For instance, the system Rehab Reader [39] leveraged squeeze sensor to help stroke patients practice squeezing while reading novels and the system Chess [39] motivates patients to squeeze while playing the chess. In the SCRIPT project 46] used several sensors to measures finger flexion, wrist angle, and velocity and orientation of the hand. The ArmeoSensor system [53] leveraged three sensors to measure acceleration, angular velocity and the magnetic field in three dimensions. Besides the above mentioned motion sensors, physiological sensors have been deployed to record body temperature, respiratory rate, pulse rate, blood pressure, etc. during the therapy process [55]. Measuring and quantifying patients' exercise movement in the home environment is beneficial when the physical help from a therapist is absent. Patients' performance of therapeutic exercises recorded by sensors could provide suggestions for patients and patient-therapist communication. Key challenges of using sensor based technologies for home rehabilitation is to minimize the obtrusiveness of sensors [55] and validate the accuracy of home-based exercises [46].

3.3.6. Tablets

[38,39] mainly refer to mobile devices such as tablet PCs and iPads. Digital Music Instruments [37] leverages an iPad app to sync users' performance when using the digital drum pads to exercise the hand and the arm. In Rehab Reader [39], a tablet PC was used to help patients conduct exercises while reading novels; and the Ball Funnel [38] system used a tablet PC to display the exercises to patients. Tablets provide a commercially available and relatively affordable form of technology that allows users to directly interact with and connect with sensors [57]. Post-stroke impairments such as visual field loss or motor deficits might be barriers for stroke survivors to interact effectively with tablets [57].

3.4. User studies

The details of the study length, study design (quantitative, qualitative, or mixed-methods), number of participants, and participant demographics are listed in Appendix B. The majority of studies employed a quantitative research design (N = 12) [27,33–37,40,47,52–55]. The systems were mostly evaluated by controlled studies, sometimes named as feasibility study or random controlled trial in the articles. Participants first received a pre-study evaluation of their physical functionalities with a given set of measurements, used the systems for a designated period of time, and then received another set of measurement during and after the system usage. Two studies adopted a qualitative design to evaluate the subjective feedback of the systems [24,32,39]. A mixed methods design that combines both quantitative and qualitative evaluation was used in 10 projects [23,26,28–30,38,43,46,49,50].

3.5. Study findings

Overall, the quantitative and qualitative findings of the studies show that home-based technologies offered unique opportunities and benefits to deliver rehabilitation to patients at home. First, some studies found that users had improved motor skills after the intervention [24,27–30,33–35,37–40,46,48,53,54], and that home-based rehabilitation technologies offer equivalent quality as conventional therapies [55]. In the 12-week study by Chen et al. [55], both the home based telerehabilitation and conventional rehabilitation groups demonstrated significant effects within groups with three time points in increasing Modified Barthel Index, Berg Balance Scale. In the HAAPI project, Wolf et al. [23] compared the efficacy between Hand Mentor Pro only and that integrated with telemonitored robotic-assisted therapy. In an eight-week trial with 99 participants randomly assigned to one of the conditions, they found both groups demonstrated improvements across all upper-extremity outcomes. A two-week study by Carey et al. [34] comparing telerehabilitation with repetitive tracking movements and simple movements with 20 participants found that the participants in both conditions showed significant improvement in the Box and Block and Jebsen Taylor tests while participants in the tracking group improved significantly in Box and Block test, Jebsen Taylor test, finger range motion, and finger-tracking activation paradigm during fMRI.

However, some studies did not show significant difference between technology-supported and conventional rehabilitation. For example, Adie et al. [42] used a mixed method to study Ninetendo and Wii sports for 6 weeks with 240 participants (122 in experiment group and 118 in control group). No significant difference was found in the primary or secondary outcome of affected arm functions at six weeks follow-up. Wii was not superior to arm exercises in home-based rehabilitation for stroke survivors with arm weakness.

Qualitative findings also show that patients demonstrated observable improvement in physical performance and the activities of daily living [32,38]. For example, in Balaam et al.'s study, some participants reported visible improvement in finger control, elbow and shoulder movement [39]. In a study by Kirk et al., some participants could transfer physical improvements into daily tasks, such as "putting on socks easier" and "dressing easier38]." Second, some studies reported participant perceived improvement in cognitive abilities [32,38,39], such as being able to "remember stuff [38]" and improved "levels of concentration [39]." Third, some participants felt the system helped reduce their social isolation. In a case study [30], since the patient started to use the system, her grandson observed her playing the games and joined the game, and they started to play together more often. Last but not least, participants reported a sense of control over their rehabilitation and appreciated the flexibility of scheduling [32,50] the day and time to exercise [50].

Meanwhile, qualitative findings also reveal two practical factors to consider in designing home-based rehabilitation technologies: patients' physical space and technical proficiency. Studies suggested the importance of selecting a place for training, such as placement of furniture and lighting condition [50]. Sometimes the size and placement of the rehabilitation system [32] made it difficult for some patients and their family members to move around the home. Patients might discontinue using the systems that take too much space in the home [38]. Patients and therapists also experienced frequently encountered technical problems, such as using a motion tracking system [50], following the necessary steps to shut down a system, and charging the system battery [24]. Particularly, it is most crucial to provide technical support in getting started with the system. Some patients needed technical assistance from family members at home or therapists over telephone [50]. In some projects, researchers have considered the potential technical issues and intentionally spent more time in the sessions in the first week to avoid technical issues [54].

4. Discussions

A few studies also summarized challenges of designing technologies for the home environment, which is different from the clinical context [39]. First, in the clinical environment, therapists use standardized approaches to guide patients through therapy and to motivate patients to engage in rehabilitation therapy; in the home environment, however, the physical absence of therapists often leads to a lack of structured sessions and so reduced patient engagement in rehabilitation. Therefore, engaging patients in exercising in the home environment remains a challenge. Second, treatment in the clinical environment is able to focus in a patient's functional needs and recovery; by contrast, home-based therapies require additional consideration of a broader range of complex factors such as patients' home environment, social context, and life experiences. Therefore, home-based therapies carry the need to consider the patients' requirements, such as the social environment in which the patient lives, practical challenges of daily lives, and their skill in use of various technologies. Based on the technology design and the study findings, we summarized the following factors that were considered crucial for designing home-based rehabilitation technologies.

4.1. Design for engagement

Different from clinical based rehabilitation sessions that are guided by healthcare professionals, home-based therapies require patients to regularly conduct exercise by themselves. In order to provide engaging rehabilitation exercises, which could be repetitive and difficult for patients, studies have integrated both *external* motivation to provide entertaining and fun experience and *internal* motivation to adapt to patients' progress.

4.1.1. External motivation

The most commonly used external motivation is to integrate virtual reality and games make the repetitive rehabilitation exercises fun and entertaining [23,24,26,29,31,35,37,40,42,46,49,50,53,54]. However, the motivational effect of games might wear off over time [22]. Some studies address this issue by increasing the *variability* of games and by adapting the game difficulty over time or meeting individual needs with consideration of a person's physical and mental levels of functioning [50]. For example, one article presented the design of different systems intended to meet each patient's individual personal interests, such as reading, playing chess, and having quality time with family members [39].

4.1.2. Internal motivation

The internal motivation aims to encourage patients with their progress. As patients begin to see improvements, the motivation shifts from external to internal motivation of expecting the system to support personal goals. A number of projects indicated that participants were most willing to conduct rehabilitative exercises when they see their progress [32,38]. When patients achieve progress over time, systems may further motivate patients by adapting the exercises to the right levels, such as increasing the length of each session and the intervention duration [24] and tailoring their personal rehabilitation goals [22,26]. Of course, these approaches are of less value if a patient is not making progress over time.

However, there is no definite boundary between external and internal motivation. When introducing game elements to encourage exercise and progress in tele-rehabilitation, elements such as badges and milestones can be considered as external motivation, but the progress associated with these virtual milestones can be considered as internal motivation. Furthermore, when patients share their progress with therapists or family members, the internal motivation might become external as well. In actual usage of the systems, whether a particular element of system design is used as internal or external motivation is dynamically changing based on patients and conditions when using the system. While it is hard to cut a clear line, system designers, developers, and other stakeholders should consider both internal and external motivation to engage patients to take an active role.

4.2. Design for the home environment

4.2.1. Social context

Since patients usually live in the family environment, the system needs to be acceptable both to the patients and other members in the family [32,39]. For example, one study emphasized the role of caregivers in stroke recovery [32], while another, using the Ball Funnel rehabilitation system, allowed the patient to play games with her son [39]. A case study [22] indicated that incorporating activities that allow participants to compete with family members might facilitate compliance and reduce patients' social isolation [30]. Therefore, it is necessary to consider the family and social environment when patients conduct therapy exercises at home.

4.2.2. Practical challenges

It is crucial to consider the practical challenges of patients and their families, e.g., time management and space requirement. Time management has been reported as a concern for patients who are assigned rehabilitation therapy sessions daily, e.g., five days per week [26]. Patients occasionally reported difficulties with fatigue and physical pain and found it more difficult to engage with the game when they are tired [24,41,58]. Besides time and life factors, studies also suggest considering the requirements of physical space, such as space requirements, placement of furniture, lighting condition [50].

4.2.3. Technical proficiency

In contrast to the clinical environment, where medical devices are operated by healthcare professionals, home-based technologies generally require a patient to operate a system without help. Therefore, it is imperative that patients are able to use a rehabilitation system without technical barriers. Helping patients overcome technical barriers is emphasized in a number of projects [22,24,41,50]. Particularly, it is most crucial to provide technical support in getting started with the system.

5. Conclusion

This systematic review provides a taxonomy of technologies designed for home-based stroke rehabilitation: games, telerehabilitation, robotic devices, virtual reality, sensors, and tablets. Based on the analysis of the user studies, home-based technologies for rehabilitation could offer multiple benefits: improving patients' motor skills, offering equivalent rehabilitation quality as conventional therapies, enhancing patients' activities of daily living, providing patients a sense of control of rehabilitation and the convenience to perform rehabilitation at home. The main challenges of technologies for home-based stroke rehabilitation include the occasionally insufficient consideration of complex factors in the home environment. Therefore, we propose designing for engagement that provide external and internal motivation and for the home environment such as the social context, practical challenges, and technical barriers.

Authors' contributions

YC1, KTA, and JTJ conducted the primary literature search, reviewed the articles and conducted the analysis. YC1 wrote the first draft of the manuscript, and KZ, SCC, YC2 contributed to the final version.

Conflicts of interest

Dr. Cramer has consulted for Roche, Dart Neuroscience, and MicroTransponder.

Summary points

What was already known on the topic?

- Information technologies systems designed for stroke rehabilitation.
- Systematic review on using robotics, virtual reality devices, games, sensors for stroke rehabilitation.

What this study added to our knowledge?

- A taxonomy of information technologies that are potential in offering home-based stroke rehabilitation.
- Designing for motivation and home environment as important requirements for home-based stroke rehabilitation technologies.

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Appendix A

To refer to technologies, we iteratively decided on a list of technical terms used in the literature and the related work or their variants. Eventually, we used the following search terms or their variants: technology, communication, telerehabilitation, telestroke, Kinect, virtual reality, augmented reality, robot, mobile, smartphone, games, computer, teleneurology, telemedicine, telecare, telehealth, telediagnosis, telemonitor, teletherapy, telehomecare, teleconsultation, remote consultation, remote supervision, remote monitoring, remote evaluation, e-health, e-therapy, e-diagnosis, e-intervention, internet-based, televideo, video-teleconference, televideo, video consultation.

Appendix B

Table B1
Summary of benefits and limitations of respective technologies for home-based rehabilitation.

Technologies	Benefits	Limitations
Games	Makes repetitive exercises more engaging and motivating	General commercial games might not be tailored for rehabilitation purposes
Telerehabilitation	Provide flexibility for patients who were underinsured, having difficulty with transportation, dependent on caregivers, or lacking stroke rehabilitation programs in their geographic areas [23].	Lacks of physical interaction between patients and therapists; Requirements of technical proficiency to use some telerehabilitation services; Uncertainties regarding policy challenges, e.g., the cost, reimbursement, privacy, liability, system security [23].
Robotic Devices	Provide automating therapy procedure and generate a wide variety of forces and motions for training; Deliver measurable and optimal dose and intensity [23] and providing repetitive practice for intensive therapy.	Sometimes require large physical space in the living environment; Sometimes need appropriate facilitates for setup; some robotic devices raise question of safety concerns when used unsupervised in the home.
Virtual reality	Provides a safe and controlled virtual environment that mimics the real clinical and daily life scenarios.	Challenge in validating the clinical outcome of using virtual reality devices that are not specifically designed for rehabilitation; sensory feedback, so critical to brain plasticity and rehabilitation therapy gains, can be altered or reduced with virtual reality approaches
Sensors	Serve as a measuring device to quantify the accuracy of patients' exercise movement. Patients' trajectory of therapeutic exercises recorded by sensors could serve as an effective means to provide suggestions for patients and patient-therapist communication.	Challenges in minimize the obtrusiveness of sensors [55] and validate the estimation accuracy of home-based exercises [46].
Tablets	Provide a commercially widely available and relatively affordable form of technology.	Might be challenging for stroke survivors with certain impairments such as visual field loss or motor deficits.

Appendix C

Table C1

Table C1
Home-based rehabilitation system and study design.

Project	Country	Year	System name	Technology	Study type	Length of intervention	#participants (who completed study)	Time since stroke before the study
P1 (Sivan et al. 2014 [37])	UK	2014	hCAAR	Robotic device games	Quantitative	8 weeks	19 (17 completed)	> 1month
P2 (Kirk et al. 2016 [38])	UK	2016	Digital musical instruments	Tablets Sensors	Mixed	5 weeks	3	> 11 months
P3 (Balaam et al. 2011 [39])	UK	2011	Rehab Reader, Chess, Exercise Instructor, Ball Funnel	Tablet PC; sensors Tablet PC; sensors; sensors	Qualitative	7 months, 6 weeks 4 weeks 7 weeks	4 (1 participant per system)	4 years, N/A 3 years, N/A
P4 (Standen et al. 2015 [41], Standen et al. 2017 [40])	UK	2015 2017	Virtual Glove	Virtual reality Sensors Games	Mixed	8 weeks	27 (17 in intervention group, 9 completed, 10 in control group, 9 completed)	Median: 22 weeks in intervention; 12 weeks in control
P5 (Adie et al. 2017 [42], Wingham et al. 2015 [43])	UK	2015 2017	Nintendo Wii Sports Wiimotes	Sensors Games	Mixed	6 weeks	240 (118 in control, 102 completed at six weeks, 97 completed six months; 117 in intervention, 102 completed)	Within the previous 6 months
P6 (Nijenhuis et al. 2015 [44], Nijenhuis et al. 2017 [46])	UK, Italy, Netherland	2015 2017	SCRIPT (Supervised Care and Rehabilitation Involving Personal Telerobotics)	Robotic device Games	Mixed	6 weeks	24 [44] 20 [46] (10 in control, 10 in intervention)	Chronic
P7 (Lemmens et al. 2014 [47])	Netherlands	2014	Haptic Master and Actiwatch	Robotic device	Quantitative	8 weeks	16 (8 in control, 8 in Haptic Master intervention group)	Chronic
P8 (Backlund et al. 2011 [48], Slijper et al. 2014 [49])	Sweden	2011 2014	Elinor	Games	Mixed	5 weeks	5 [48]; 12 (11 completed) [49]	Chronic (> 11 months)
P9 (Palmcrantz et al. 2016 [50])	Sweden	2016	DISKO-tool	Games Kinect sensor	Mixed	3 weeks	15 (14 completed)	All stages of continuum (1-115 months)
P10 (Piron et al. 2008 [52])	Italy	2008	N/A	VR Telerehabilitation	Quantitative	4 weeks	10 (5 in Tele-VR at home, and 5 in VR in hospital setting)	> 12 months
P11 (Wittmann et al. 2016 [53])	Switzerland	2016	ArmeoSenso	Games VR Sensor	Quantitative	6 weeks	11	5 months
P12 (Jordan et al. 2014 [54])	New Zealand	2014	N/A	Games VR	Quantitative	4-6 weeks	13 (12 completed, 11 took the final assessment)	> 6months
P13 (Chen et al. 2017 [55])	China	2017	N/A	Telerehabilitation	Quantitative	3 months	54 (27 intervention group, 24 completed; 27 in control group, 26 completed) 54(27 telesupervisingintervention group, 24 completed; 27 in control group, 26 completed)	14 to 90 days from stroke onset
P14 (Wolf et al. 2015 [23])	US	2015	HAAPI Hand Mentor Pro	Games Robotic device Telerehabilitation	Quantitative	8 weeks	99 (51 in HMP + HEP group, 47 completed; 48 in HEP group, 45 completed)	Within 6 months
P15 (Brown et al. 2014 [25], Brown et al. 2015 [24])	US	2014 2015	NeuroGame Therapy	Games, telerehabilitation	Mixed	4 weeks, 45 min, 5days/ week	12 (9 Completed); 10	> 6months
P16 (Proffitt et al. 2015 [26])	US	2015	Mystic Isle	Games Virtual reality Sensor	Mixed	6 weeks	4	> 6months

(continued on next page)

Table C1 (*continued*)

Project	Country	Year	System name	Technology	Study type	Length of intervention	#participants (who completed study)	Time since stroke before the study
P17 (Langan et al. 2013 [27])	US	2013	N/A	Telerehabilitation	Quantitative	6 weeks	7	Chronic stage
P18 (Zhang et al. 2011 [28])	US	2011	RUPERT	Robotic device VR	Mixed	4 weeks	8 (2 in the home setting; 6 in the clinic setting)	> 6months
P19 (Flynn et al. 2007 [29])	US	2007	Sony PlayStation 2 (PS2) EyeToy	Games VR	Mixed	4.5 weeks	1	17 months
P20 (Alankus et al. 2010 [31], Proffitt et al. 2011 [30])	US	2010 2011	N/A	Games Virtual reality	Mixed	6 weeks	1	17 years
P21 (Cherry et al. 2017 [32])	US	2017	N/A	Robotic device Telerehab	Qualitative	3 months	10	Different stages
P22 (Holden et al. 2007 [33])	US	2007	N/A	Telerehab VR	Quantitative	6 weeks	12	> 6months
P23 [34] (Carey et al. 2007)	US	2006	N/A	Telerehab	Quantitative	2 weeks for track and move group, 2 additional weeks for the move group	20	> 12months
P24 (Brokaw et al. 2015 [35])	US	2015	HAMSTER	Games VR	Quantitative	1 months	1	13 months
P25 (Kim et al. 2015 [36])	US	2015	N/A	Robotic devices Sensors	Quantitative	6 weeks	9	> 6months

Appendix D

Table D1

Table D1
study measures and outcomes.

Project	Measures	Measures taken	Main findings
P1 (Sivan et al. 2014 [37])	Fugl Meyer Upper Extremity motor subscale (FM-UE), Action Research Arm Test (ARAT), Medical Research Council (MRC) and Modified Ashworth Scale (MAS), Chedoke Arm and Hand Activity Inventory (CAHAI), ABILHAND	A0: beginning A1: after 8 weeks A2: after 1 month	The kinematic and clinical outcomes significantly improved after 8 weeks. Three participants showed clinically significant improvement in all the clinical outcomes.
P2 (Kirk et al. 2016 [38])	Arms lengths reach test, range of movment (ROM) in the armL shoulder ROM, elbow flexion, wrist extension, wrist flexion Time on tasks, other physical and psychological measures	A1: pretest A2: posttest (5 weeks after system use) A3: 3 months post intervention	Participants demonstrated significant increase in self-management and functional measures and reduction in time on tasks. Participants reported transferring physical improvements into tasks of daily living and enhanced memory.
P3 (Balaam et al. 2011 [39])	N/A	N/A	It is essential to design technologies that motivate individual patients, balances between work, duty and fun, support motivation over time, and understand the wider social context
P4 (Standen et al. 2015 [41], Standen et al. 2017 [40])	Wolf Motor Function Test, Nine-Hole Peg Test, Motor Activity Log and Nottingham Extended Activities of Daily Living	A1: baseline A2: after 4 weeks A3: final usage	Significant change from baseline in the intervention group on midpoint Wolf Grip strength and two subscales of the final Motor Activity Log. Participants found the games motivating to use, liked the family support; barriers of using the system mainly include: technical issues, dependency on someone to help with the device, health problems, competing commitments in life
P5 (Adie et al. 2017 [42], Wingham et al. 2015 [43])	Action Research Arm Test; Secondary outcome measures: Canadian Occupational Performance Measure, Stroke Impact Scale, Modified Rankin Scale, EQ-5D 3L	A1: pretest A2: (posttest) after 6 weeks A3: (follow-up) after 6 months	There was no significant difference in the primary or secondary outcome of affected arm functions at six weeks follow-up. Wii was not superior to arm exercises in home-based rehabilitation for stroke survivors with arm weakness.
P6 (Nijenhuis et al. 2015 [44], Nijenhuis et al. 2017 [46])	Stroke Impact Scale, Fugl-Mayer Scale, Action Research Arm Test, Motor Activity Log [44] Action Research Arm Test, Intrinsic Motivation Inventory, Fugl-Meyer, Motor Activity Log; Stroke Impact Scale and grip strength [46]	A1: pre test A2: post test (6 weeks later) A1: one week before A2: one week after training; A3: two months after training	Participants demonstrated improvement in Stroke Impact Scale. Patients found that their duties in the life and family could be a hinder to their usage [44]. The control group reported a higher training duration; Perceived motivation was positive and equal between groups. Motivation during training was positive in both groups. Both groups showed moderate improvements on most clinical assessments. No demonstration of additional benefit of technology supported rehabilitation [46].
P7 (Lemmens et al. 2014 [47])	Arm accelerometry data, FMMA, Action Research Arm Test (ARAT) and MAL	T0: baseline T1: 4 weeks after training T2: end of the 8 weeks training T3: 6 months after finishing the program	Duration and intensity of use of the affected arm-hand did not change significantly during and after training, with or without robot-support No significant between-group differences were found.
P8 (Backlund et al. 2011 [48], Slijper et al. 2014 [49])	National Institutes of Health Stroke Scale, measures of active moment, finger-nose test, Modified Ashworth test, Action Research Arm Test (ARAT), Assessment of motor and process skills, Motor Activity Log (MAL) [48] FMA-UE,ABILHAND, ARAT, Fugl-Meyer, grip force (GrippitR) and ARAT, ABILHAND [49]	A1: before experiment A2: 5 weeks after [48] A1: baseline B: during intervention once a week A2: post-test measure C: follow-up 16-18 weeks [49]	Improvement in assessment of motor and process skills,; self-reported improvements in motor activity logs. Fun was perceived as positive for motivation and Elinor as a tool to engage family members also provided motivation [48]. FMA-UE A-D (motor function), ARAT, the maximal grip force and the mean grip force on the affected side show significant improvements at post-test and follow-up compared to baseline [49].
P9 (Palmcrantz et al. 2016 [50])	NIHSS, Birgitta Lindmark motor assessment, Modified Ashworth Scale, Berg Balance Scale, Functional Ambulation Categories, ontreal Cognitive Assessment, Barthel Index, EQ-5D VAS	A1: before the intervention	It is crucial to select a place at home for training, learn how to use the tool and how to perform the exercises, receive the training at the right level, receive real-time feedback of performance, resolve technical problems.
P10 (Piron et al. 2008 [52])	Fugl-Meyer UE	A1: pretest A2: posttest	The comparative study: patients in the Tele-VR group was equal to or higher than the VR group in all 12 measurements. In motor performance, the Tele-VR group improved significantly, but not the VR group. Patients in the Tele-VR group were able to engage in therapy at home and the telerehab system helped establish a good relationship between the patient and the therapist.
P11 (Wittmann et al. 2016 [53])	Self-selected dose of training with ArmeoSenso FMA-UE, WMFT, IMU-derived kinematic metrics	A1: before the start A2: after three weeks A3: after six weeks of training	Patients' arm function (FMA-UE) significantly improved significantly. Changes in the WMFT were not significant ($p = 0.552$)
P12 (Jordan et al. 2014 [54])	Upper limb component of the FMA-UL, Intrinsic Motivation Inventory (IMI)	A1: after enrollment A2: 4 week after A1 A3: within 1 week of finishing intervention A4: 4 weeks after A3	An average increase in the FMA-UE after intervention.

(continued on next page)

Table D1 (*continued*)

Project	Measures	Measures taken	Main findings
P13 (Chen et al. 2017 [55])	Modified Barthel Index, Berg Balance Scale, modified Rankin Scale, Caregiver Strain Index, root mean square of ex- tensor carpi radialis longus and tibialis anterior muscle	A1: baseline A2: 12 weeks after A1 A3: 12 weeks after A2	Significant increase in Modified Barthel Index, Berg Balance Scale, and decrease in Caregiver Strain Index, but differences between groups was significant. For modified Rankin Scale, the percentage of participants of grades 0 and 1 in both groups increased, but no significant difference between the groups.
P14 (Wolf et al. 2015 [23])	ARAT, WMFT, FMA	A1: pre test A2: post test	In the larger study, both groups demonstrated improvement across all upper extremity outcomes. Some participants found the system effective and adhered to the rehabilitation. Meanwhile, family and life role responsibilities occasionally hindered the compliance.
P15 (Brown et al. 2014 [25], Brown et al. 2015 [24])	Duration of system use, sEMG, Wolf motor Function test, Chedoke Arm and Hand Activity Inventory	A1: about 8 weeks prior to system use A2: about 4 weeks prior to system use A3: immediately after completion of system use.	Participants demonstrated significant improvements in game play and sEMG outcomes. Participants found the system engaging and motivating, but observed minimal functional upper extremity improvement.
P16 (Proffitt et al. 2015 [26])	FMUA, COPM, Balance Confidence Scale, Activities-Specific Balance Confidence Scale, Stroke Specific Quality of Life Scale	A1: before intervention A2: after 6 weeks (post-intervention)	Two participants reported an increased ability in the self-care domain on the Stroke-Specific Quality of Life scale; one participant had an increase in COPM satisfaction score. Participants enjoyed the games that tailored to help them achieve their goals and motivated by motor + cognitive challenges. They reported barriers in time management.
P17 (Langan et al. 2013 [27])	WMFT, Groton Maze Learning test	A1: before intervention A2: after 6 weeks (post-intervention) A3: one month after A2	Improvements in clinical and kinematic assessments; movements of the more affected arm were smoother at post-testing and scores were more similar to those of the less affected hand; five participants demonstrated a reduction in streamlined WMFT performance; enhanced tactile discrimination performance in the less affected hand and trended towards improvement in the more affected hand; five participants demonstrated a trend toward improved cognitive performance in the Groton Maze Learning Test.
P18 (Zhang et al. 2011 [28])	Wolf Motor Function Test, FMA	A1: before intervention A2: after intervention	The two patients in the home setting demonstrated functional improvement and significant increase in the movement smoothness on reaching some target.
P19 (Flynn et al. 2007 [29])	Fugl-Meyer Assessment, Upper Extremity Functional Index, Beck Depression Inventory, Berg Balance Scale, Dynamic Gait Index, Mini-Mental State Exam, Timed Up and Go, Six-Minute Walk Test, Motor Activity Log Modified Ashworth Scale Functional Reach Test	A1: (pretest) before intervention A2: (midtest) after 10 sessions A3: (posttest) after 20 sessions A4: 6 months after intervention	Significance in Dynamic Gait Index and trends toward improvement on the Fugl-Meyer Assesment, Berg Balance Scale, UE Functional Index, Motor Activity Log, and Beck Depression Inventory. The participant purchased her own equipment and continued to play on a regular basis with her family members together.
P20 (Alankus et al. 2010 [31], Proffitt et al. 2011 [30])	Action Research Arm Test (ARAT) Activity Card Sort (ACS) Reaching Performance Scale (RPS)	A1: before the study A2: during the third week A3: during the sixth week	After three weeks, the participant demonstrated increased range of motion at the shoulder and decreased compensatory trunk movements during reaching tasks. After six weeks, she showed functional improvement in shoulder rotation range and activities of daily living. Participant also reported enhanced ability to move the affected arms, large range of motion and feeling of control, and ability to perform daily tasks.
P21 (Cherry et al. 2017 [32])	N/A	N/A	Participants reported the systems to be convenient, enhance their mobility and mood, and served as an outlet for their physical and mental tension. However, they found it inconvenient to place the device and faced occasional technical issues.
P22 (Holden et al. 2007 [33])	Fugl-Mayer-UE, Wolf Motor, shoulder flexion strength, grip strength	A1: pre-training A2: post-15 sessions A3: post-30 sessions, A4: four months follow-up	Participants demonstrated significant improvements in Fugl–Meyer and Wolf motor test and a trend of improvement for grip strength. The improvement were mostly maintained at four-months follow-up.
P23 (Carey et al. 2007 [34])	Box and Block test, Jebsen Taylor test, and finger range of motion, along with a finger-tracking activation paradigm during fMRI.	A1: pretest A2: posttest A3: follow-up	The track group demonstrted significant improvement in all behavioral tests; the move group showed improvement in the Box and Block and Jebsen Taylor tests.
P24 (Brokaw et al. 2015 [35])	Stroke Impact Scale-16, Fugl Meyer, Jebsen Taylor	A1: before-training A2: after-training	The participant has demonstrated improvement on all the measures after one month of use.
P25 (Kim et al. 2015 [36])	Modified Ashworth Scale, Box and Blocks test, FMA-UE, Arm Motor Ability Test, and Motor Activity Log-Amount of Use and Motor Activity Log-How Well subscales	A1: before-training A2: after-training but before the home program A3: after the home-based program A4: 12-week follow-up after the home program	Participants showed significant improvement on the measures of FMA-UE, MAL-AOU, MAL-AOU

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